On The Time-Dependent Internal Energy Budgets of the Tropical Warm-Water Pools

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November 25, 2002

Submitted to the *Journal of Climate*

Abstract

The exchange of internal energy between the warm water pools of the tropical oceans and the overlying atmosphere is thought to play a central role in the evolving climate system of the earth. Spatial displacements of the warm water pools are observed on annual and interannual time scales, the latter most notably in the Pacific in association with ENSO. We investigate whether such variations are also associated with net changes in pool energy content. Our study extends the work of Niiler and Stevenson (1982) and Walin (1982) who considered the time mean energy budgets for volumes bounded by an isotherm. We analyze the time-dependent version of their equation in which the main terms involve the time variation of pool volume and energy content, net energy exchange between the pool and overlying atmosphere, and the turbulent ocean flux across the pool boundary. The dominant signal in the mean seasonal energy budgets of the warm pools is an approximate balance between the annual variation of air–pool exchange and the time-varying energy storage; the inferred turbulent ocean heat flux per unit area across the bounding surface of the warm pools is relatively steady through the year. Interannual variations of the warm pools are characterized by changes in pool volumes and energy content on ENSO and longer time scales with indication of an out of phase relationship between pool energy content and the Southern Oscillation Index. Our ability to diagnose the varying turbulent ocean fluxes from the warm water pools on these time scales was impeded by incompatibilities between ocean temperature data and several air–sea flux climatologies. For the unscaled COADS flux product that yields sensibly down-gradient ocean heat flux extimates, we find strong positive correlation between air–pool heat flux and inferred turbulent ocean flux at pool base on interannual time scale. But given the uncertainties in the air–sea fluxes and lacking a physical

mechanism to explain positive correlation between air–sea and turbulent ocean fluxes, we are unwilling to firmly attribute these bottom flux changes to variations in ocean mixing processes. Though disappointing in the short term, we suggest that time-dependent warm pool energy budget analyses constitutes a powerful diagnostics for validating future air–sea flux climatologies.

1. Introduction

Energy exchanges between the oceans and the overlying atmosphere play a central role in the evolving climate system of the earth. Of particular interest are atmospheric interactions with the tropical warm water pools as these regions mark sites of intense convection in the tropical atmosphere that in turn have profound influence on tropical winds (*e.g.*, Walker, 1923, 1924; Bjerknes, 1969) and tropospheric temperatures (*e.g.*, Sobel *et al.*, 2002) as well as extratropical weather patterns (*e.g.*, Bjerknes, 1969; Horel and Wallace, 1981). Warm water pools are found in the western Pacific, eastern Pacific off Central America, equatorial and northern Indian Ocean, and the western Atlantic Ocean, as shown in Figure 1. We are interested in how the energy stores of these warm pools vary interannually in relation to climatic changes of the ocean–atmosphere system.

It is well known that ENSO (El Niño – Southern Oscillation) is manifested by a zonal sloshing of the western Pacific's warm water pool in relation to changes in the trade winds. (*e.g.*, Bjerknes, 1966a,b; Wyrtki, 1975; Cane, 1983; Rasmusson and Wallace, 1983). But in addition to spatial displacements of the warm waters during ENSO (and associated patterns of air–sea exchange), are there also interannual variations in the total internal energy (heat) content of the Pacific pool? In similar spirit, variations in monsoonal rains over the Indian subcontinent (*e.g.*, Nicholls, 1995; Saji *et al.*, 1999), Brazil (*e.g.*, Hastenrath and Greischar, 1993; Nobre and Shukla, 1996) and North America (*e.g.*, Enfield, 1996) are thought to be intimately related to changes in the adjacent warm water pools. Do the total heat content of the Indian and Atlantic pools vary interannually in concert with atmospheric changes or is their dominant mode of variability chiefly an adiabatic sloshing with corresponding spatial shifts in the patterns of air–sea exchange? Complicating assessment of energy storage and exchange between the atmosphere and warm pools, we note that heat is lost from the warm water pools by mixing with the colder underlying waters. Are these turbulent ocean fluxes steady in time or does the mixing also vary? We set out to explore these questions through an analysis of climatological data.

In 1982, Niiler and Stevenson (and later, Zhang and Talley, 1998) looked at the time mean heat budgets for the tropical warm water pools using the clever technique (also discussed by Walin, 1982) of writing the budget for waters bounded by a specified isotherm. When so expressed, mean advection in and out of such a control volume does not contribute to the mean heat budget of the volume. This analysis technique has since been exploited by Speer and Tziperman (1992) and Speer *et al*. (1995) among others in the study of water mass transformation. Subsequently, Moisan and Niiler (1998) examined the seasonal cycle of local air–sea exchange, arguing (after Gill and Niiler, 1973) for a first order balance between surface heat exchange and local storage change at annual period. Their approach used the observed annual cycle of upper-ocean temperature to validate/ correct bulk-formulae-based estimates of air–sea heat exchange for regions where advection was not a major factor.

Here we explore a combination of these two approaches, specifically, we diagnose the time-dependant heat budgets of the tropical warm water pools bounded by specified isotherms. A strength of this approach is the fact that ocean advective terms, always difficult to estimate, do not appear in the budget equation. As such, the work is complementary to drifter-based Lagrangian studies such as Ralph *et al.* (1997) and relates to more traditional Eularian analyses by Wang and McPhaden (1999), Cronin and McPhaden (1997) and Weller and Anderson (1996) among many others, and to direct air–sea flux observations by for example, Fairall *et al*. (1996). Our analysis also has relationship to the work of Meinen and McPhaden (2000, 2001) who investigated volumetric variations in the Pacific waters having temperatures warmer than 20ºC, but bounded meridionally by latitude lines (not the isotherm outcrops used here) and Wang and Enfield's (2001, 2002) studies of the “Western Hemisphere Warm Pool.”

Mathematically, our analysis starts with the approximate internal energy (heat) equation:

$$\rho c_p D\Theta/Dt = \nabla \cdot \mathbf{F_h} \tag{1}$$

where the right hand side of the equation holds the divergences of the turbulent and radiative heat fluxes including the air–sea exchange terms, Θ is the potential temperature and ρc_p is the sea water density and specific heat, respectively (both taken as constant here). Integrating the above equation over a volume, V, defined by the instantaneous position of an isotherm ($\Theta = \Theta_x$), applying Liebnitz's rule on the left and Gauss' Theorem on the right and shifting terms yields:

$$D/Dt \int\int\int \rho c_p\, \Theta\, dV = \rho c_p\, \Theta_x\, DV/Dt + \int\int \rho c_p (SST-\Theta_x)(P-E)\, dA + \int\int \mathbf{F_h} \cdot \mathbf{n}\, dA\, . \tag{2}$$

In words, this equation relates the rate of change in the volumetric pseudo heat content of a warm pool to the time rate of change in its volume, and the fluxes of heat through the bounding surface defining the pool. The second term on the right, arising from fluxes of water by precipitation and evaporation (P–E) through the free surface (whose temperature, SST, may depart from Θ_x) is small compared to the other terms and is neglected in what follows by fiat. (The latent heat flux is not small and is retained in the $\mathbf{F_h}$ term.) The third term on the right hand side has several contributions:

$$\int\int \mathbf{F_h} \bullet \mathbf{n}\, dA = \int\int F_s\, dA_s - \int\int F_p\, dA_s - \int\int F_b\, dA_b\,. \qquad (3)$$

These are the net air–sea radiative, sensible and latent heat fluxes (F_s) integrated over the surface area of a warm pool (A_s), the penetrative shortwave radiative flux across the base of the pool (F_p), and the turbulent ocean heat flux across the base and sides of the pool (F_b) whose surface area is A_b.

Previous studies looked at the time-mean of equation (2), in which the balance is between the mean air–sea heat flux integrated over the mean extent of a warm pool and the diffusive ocean fluxes across the mean position of the bounding isotherm (equation 3 set equal to zero). Niiler and Stevenson (1982) demonstrated that on average, the tropical warm water pools gain heat from the atmosphere and lose heat (thought chiefly by diapycnal diffusion) to the underlying colder waters. Here we are interested in the time-dependent problem. As equation (2) shows, any unbalanced air–sea heat flux into a warm water pool (*e.g.*, a period when a change in the net surface flux is not compensated by a corresponding change in turbulent ocean heat flux) is reflected in a change in the pool's volume and/or pseudo-heat content. Ocean temperature data allow estimation of the first two terms in equation (2), while air–sea heat flux climatologies are available to estimate the first and second term on the right side of equation (3) (the latter requiring estimation of the absorption profile). That leaves the diffusive fluxes in the ocean across the bounding isotherm. Accepting available ocean temperature and air–sea flux data, using equations (2) and (3) we obtain as the residual, an estimate of the time-varying diffusive heat flux across the warm pool bounding isotherm as a function of time. But in practice as discussed below, some combinations of presently available ocean temperature and air–sea flux data infer unphysical (up-gradient) diffusive fluxes, suggesting that these climatologies are mutually incompatible. And even in the cases where the inferred turbulent fluxes are down gradient, errors in the air–sea fluxes may dominate the turbulent flux estimates.

2. Analysis

A. Mean Annual Cycle

We initiated our study with an examination of the mean seasonal cycle of the warm water pools of the Atlantic, Pacific and Indian Oceans. Mean monthly estimates of warm water pool volumes and heat content were derived using the WOA98 (World Ocean Atlas) climatology (Conkright *et al.*, 1998). This product is the result of an objective analysis of all available, edited, temperature profile data in the National Ocean Data Center archive. For the Pacific and Indian basins, we chose pools bounded by the 28ºC isotherm, focussing our study on the waters most closely associated with deep convection in the atmosphere (*e.g.*, Zhang, 1993). For this bounding isotherm, the Indian and Pacific pools connect through the Indonesian archipelago in 6 of the 12 WOA monthly temperature distributions (not counting connections through the very shallow Malacca Strait). We therefore analyzed the budget of the combined pool volumes. (If the transport of waters warmer than 28°C through the Indonesian passages is neglected, the Pacific and Indian pools may be treated separately.) The 28ºC pool in the eastern Pacific is distinct from the western pool throughout the mean annual cycle. However, this is not the case in the monthly climatologies we examine later and so for consistency, we included the eastern pool in our IndoPacific budget. The tropical Atlantic surface waters are somewhat cooler than the waters of the other basins; we chose a 27ºC bounding isotherm there to work with a pool spanning a comparable latitudinal range.

We explored several monthly-mean air–sea flux climatologies including the SOC product (Josey *et al*., 1998), the constrained and unconstrained COADS (Comprehensive Ocean–Atmosphere Data Set — da Silva *et al.*, 1994), and monthly-mean flux estimates constructed from numerical weather model reanalyses fields (ECMWF — Gibson *et al*., 1997, and NCEP — Kalnay, *et al.*, 1996). Our base calculations for the mean annual cycle used the SOC fluxes. In all cases, the penetrative short wave fluxes through the base of the warm pools were derived from the respective surface short wave flux estimates, pool depth, and the Jerlov 1A absorption profile (Jerlov, 1976). Lacking broadscale climatological information, space–time variations in the absorption profile due to biological productivity changes (*e.g.*, Segal *et al.*, 1995) were not considered: a potential source of error in our analysis. Procedurally, each field of monthly–mean air–sea flux was mapped onto the corresponding ocean temperature grid and integrated spatially over the extent of the warm water pool for that month.

The warm pools of both the IndoPacific and Atlantic exhibit pronounced seasonal cycles with pool volumes varying by about a factor of 2 through the year (Figures 2A and 3A). Because pool water temperatures never greatly exceed the pool bounding values, the volume and pseudo heat content curves tend to parallel each other. (These pseudo heat content estimates displayed in Figures 2 and 3 are derived on the Centigrade temperature scale; thus only changes in this variable with time have physical meaning.) As one might expect, the warm pools in all three ocean basins expand and contract meridionally with the seasonal heating and cooling cycles in the respective hemispheres (Figure 1). Semi-annual behavior in pool volume and heat content manifests this periodicity in incident solar energy about the equator. Hemispheric asymmetries in the western Atlantic and Pacific boundaries and the corresponding continental influence on regional air–sea exchange give rise to the annual-period signals in total pool volume and pseudo-heat content in these basins that are phased with the northern hemisphere (warmest waters in mid-to-late boreal summer). In contrast, the limited geographic extent of the North Indian Ocean results in the southern hemisphere driving the pool seasonal cycle in this basin (greatest pool volume and pseudo-heat content in April). Redistribution of surface waters in the Indian Ocean in response to monsoonal surface winds and coastal upwelling act along with the time varying air–sea heat exchanges to produce the more complex geometric seasonal evolution of the warm pool in the Indian Ocean as compared to other two basins (Figure 1). Note however that advection alone does not affect the integrated pool volume or heat content. Despite it's greater mean volume, the seasonal range of the Pacific pool volume and heat content are comparable to those of the Indian, and the phasing of the summed IndoPacific warm pool tends to follow the Indian's annual cycle, Figure 2A.

The first two terms in (2) are by far the largest but they have the same sign and appear on opposite sides of the equation. Thus it is the difference of the two heat content terms that relates to the turbulent flux divergences. This difference (the time-rate-of-change of internal energy integrated over the IndoPacific and Atlantic pools) exhibits semi-annual periodicity, Figures 2B and 3B respectively. In the Atlantic, the integrated energy content change is positive in late boreal winter and mid-summer and negative in late spring and fall. The phasing for the corresponding IndoPacific curve is similar in character but lags the Atlantic's by about one month. As indicated above, this semi-annual behavior is driven by the air–sea heat flux. Both the integrated heat flux from the atmosphere into the two warm pools (Figures 2B, 3B) and the flux per unit area (Figures 2C, 3C) have two maxima and two minima through the year. The penetrative short wave heat flux across the base of the pools is relatively steady through the year. In addition, the inferred total turbulent heat flux and flux per unit area across the boundaries of the warm pools are relatively constant in time. (Inferred as a residual, the turbulent flux term also contains the summed errors of the other quantities in equation 2.) Specifically, the climatological seasonal variations in bottom heat flux are less than 15% of the annual-mean bottom flux for both pools. If we assume, following Niiler and Stevenson (1982), that these bottom fluxes are chiefly attributable to diapycnal mixing, an effective diffusivity of order 1 $cm^2\ s^{-1}$ is deduced (Figures 2D, 3D). While large in comparison to the diffusivity estimated for the main thermocline (*e.g.*, Gregg, 1998; Ledwell *et al.*, 1998; Polzin *et al.*, 1995), we note that the warm pool base frequently lies at or just below the base of the surface mixed layer where enhanced mixing is frequently observed (*e.g.,* Moum and Smyth, 2001). However, it is also likely that significant turbulent flux out of the warm pools is accomplished by lateral processes (*e.g.*, mesoscale eddies and/or mixed layer processes) for which the above vertical mixing parameterization is inappropriate.

We find that, consistent with Gill and Niiler (1973) and the local analyses of Moison and Niiler (1998), on seasonal time scale the dominant temporal balance in the tropical warm water pools is between variations in air–sea exchange and changes in heat storage. These annual variations are superimposed on the time–mean balance between heat input to the pools across the air–sea interface and turbulent flux across the pool ocean boundaries.

The above seasonal analysis was developed with the SOC air–sea heat flux climatology. Consistent results based on these fluxes might be expected given that the SOC climatology is based on bulk formulae tuned with direct flux estimates from the western Pacific warm pool (*e.g.*, Fairall *et al.*, 1996). For comparison, and looking forward to our interannual analysis that required monthly flux estimates, we also constructed energy budgets with the annual COADS climatology (constrained and unconstrained) of da Silva *et al.* (1994) and with mean monthly flux estimates from the two weather model reanalyses projects: NCEP (Kalnay *et al*., 1996) and ECMWF (Gibson *et al*., 1997). As evidenced by Figure 4, the model reanalysis fields and constrained COADS climatology (in which the fluxes have been adjusted so that the time–mean globally integrated air–sea heat flux is zero) underestimate the transfer of heat from the atmosphere into the tropical warm water pools relative to the SOC product. Carrying the mean-annual heat budget analyses forward with these alternate flux products leads to the unphysical requirement for up-gradient turbulent ocean heat fluxes across the pool bases during parts of the year (not shown). (For example, the monthly inter-annual energy budget analysis for the IndoPacific warm pool derived, as described below, with the constrained COADS fluxes returned negative inferred turbulent diffusivity estimates 36% of the time.) We conclude that the constrained-COADS, NCEP and ECMWF fluxes are not consistent with the WOA98 ocean temperature climatology in the tropical warm water pool regions. Discrepancies in the reanalysis flux products have been documented previously, based on local heat budget calculations (*e.g.* Cronan and McPhaden, 1997; Anderson *et al.*, 1996) and in comparison with buoy data (*e.g.* Weller *et al.*, 1998). Mean annual pool budget analyses with the unconstrained COADS fluxes are better behaved and essentially indistinguishable from those based on the SOC fields. As there is no monthly SOC heat flux product yet available, our interannual analysis was restricted to using the unconstrained COADS flux estimates, available for the period 1945 through 1993.

B. Interannual Variability

In similar spirit to the above study of the mean annual cycle, we initiated our interannual analysis by accessing two available monthly ocean temperature climatologies having global coverage (apart from the polar regions). The first product, described by White (1995), consists of a space–time objective mapping of quality-controlled *in situ* ocean temperature data. (The gridded fields were accessed from the SIO Joint Environmental Data Analysis center website: http://jedac.ucsd.edu.) This data product is binned with resolution in the horizontal of 5° longitude by 2º latitude and 20 m in depth to 80 m (with 40-m resolution deeper). We worked with monthly gridded fields spanning the period 1960 through 2000, linearly interpolated to 1-m vertical resolution and 1º × 1º horizontal resolution. The second temperature climatology is the result of a data assimilation model as described by Carton *et al.* (2000ab) and Chepurin and Carton (1999). Model data were acquired as detailed on the website: http://meto.umd.edu/~carton/. In the tropics, the model had horizontal resolution of 2.5º longitude by 0.5º latitude and 15 m (to 150 m) in the vertical (that we also linearly interpolated as detailed above). The model was driven by COADS winds (da Silva *et al.*, 1994) supplemented by recent fields from NCEP. Again, we worked with monthly fields in this case for the period 1960 through 1999. Preliminary work with these model data within the Pacific warm pool documented offsets in derived pool area, volume and pseudo-energy content between the two climatologies, most notable after March 1993 (Carton *et al.* values smaller than White's). This discrepancy was attributed to the introduction of satellite altimeter data to the assimilation model beginning in 1991 (J. Carton, personal communication, 2002). We therefore opted to utilize output from the version of their model that excluded altimeter observations. (This product shows long-term temporal behavior consistent with the White climatology, Figures 5A, 6A.) The small persistent differences in our derived warm-pool volumetric products from the two climatologies (and between the mean annual cycles constructed from these data in comparison to the WOA98 analysis above) appear to be due to different land boundaries and spatial resolutions (horizontal and vertical) of the various gridded fields. In general, the Carton *et al*. warm pool volume and pseudo heat content estimates are smaller than White's and WOA98's by about 5%. However, the Carton *et al*.-based pool area estimates are smaller by some 35%. In addition to domain differences, these latter discrepancies are associated with the lateral margins of the warm pools where the White and WOA98 climatologies show broad, thin fringes not present in the Carton *et al*. product. We do not know if the Carton *et al.* model mixed layers in these regions are deeper (hence colder) than reality, or if the thin fringes are an artifact of the WOA and White mapping/averaging procedures. In our application, the fringe area discrepancy manifests itself as sizable differences in the derived air–pool heat fluxes based on the two ocean climatologies. While quantitative differences in our derived pool fluxes result, our basic conclusions are independent of selected ocean product.

Based on either temperature climatology, we observe that over the last 40 years, the 28ºC IndoPacific pool experienced ± 50% variations in pseudo heat content relative to the long-term mean, Figure 5. A trend is evident in the time series; the average rate of increase in the IndoPacific pool volume, estimated by a linear least-square fit with time to the 40-year record, is 0.5×10^6 m^3 s^{-1}. (The corresponding drift estimate for pool pseudo heat content of 6×10^{13} W is essentially given by the volume drift scaled by the pool bounding temperature.) But the IndoPacific pool's time history is far more complex than a linear drift. In particular, pool pseudo heat content is punctuated by an abrupt increase that occurred around 1976, a so-called climate shift seen previously in ocean and atmosphere data (*e.g.*, Nitta and Yamada, 1989; Trenberth and Hurrell, 1994; Zhang *et al*., 1997; Gunderson and Schrag, 1998; Flugel and Chang, 1999; Luo and Yamagata, 2001). The 27ºC pool in the Atlantic has similar low-frequency behavior (Figure 6). The overall trend in the Atlantic pool volume is 0.2×10^6 $m^3 s^{-1}$, also with enhanced change in the mid-1970's.

The other dominant time scale evident in Figures 5 and 6 is that of the El Niño/Southern Oscillation (ENSO) events. Surprisingly (at least to us), the pseudo heat content of the IndoPacific warm pool since 1960 has tended to vary out of phase with the Southern Oscillation Index (SOI – data obtained from NCEP: http://www.cpc.ncep.noaa. gov/data/indices/). While the maximum lag correlation coefficient between pseudo heat content (and that with linear trend removed) and the SOI is just -0.3 (marginally significant based on a 12-month decorrelation timescale), extended periods are evident (particularly from about 1965 to around 1990) when the correlation is much stronger (-0.5 for that time interval and significant at the 0.05 level). In words, this correlation implies that the Indo-Pacific warm pool is most developed (relative maximum in volume and pseudo heat content) at the height of El Niño (extreme negative SOI events) and is smallest in the midst of La Niña. During the onset of El Niño when the atmosphere is responding to strong heating anomalies associated with eastward displacements of the warmest tropical waters, the pool as a whole is gaining in internal energy. And as the ocean/atmosphere system tends back towards normal (and/or transitions to La Niña) the pool as a whole loses energy.

The Atlantic's warm pool pseudo heat content is also correlated with the SOI. After removing the record-length trend, a maximum correlation of -0.4 at a lag of 6 months (SOI leading pool heat content) is obtained (significant at the 0.05 level). Enfield and Mayer (1997) previously reported a lag corelation between Atlantic SST and ENSO. Possibly reflecting the uncertainties in dealing with short time series, the Atlantic pool also shows comparable-sized correlation with the North Atlantic Oscillation (Hurrell, 1995 – Index estimates obtained from http://tao.atmos.washington.edu/data_sets/nao/). Local correlation maxima of approximately 0.5 are obtained at a lag of 71 months (NAO leading pool volume) and 0.36 at -17 months lag.

In an attempt to understand the cause of these low-frequency pseudo heat content variations, we explored the interannual variations in the pool energy budgets, following the same analysis procedures as for the mean annual cycle using the White ocean temperature climatology and the unscaled COADS air–sea fluxes (Figures 5 and 6). At these longer periods, the dominant terms in the pool energy budgets are different than for the annual cycle (where air–pool heat flux anomalies chiefly induced change in heat storage). Not surprisingly given that both scale strongly with pool area, the variations in total air–pool heat flux and inferred total turbulent bottom flux are correlated. But even after normalizing by pool area (Figure 5C), we find that the air–sea heat exchange between the IndoPacific pool and atmosphere has comparable standard deviation (6.5 W m^{-2}) to that of the inferred turbulent bottom flux per unit area (6.9 W m^{-2}), with both larger than the standard deviation of pool energy content change (4.3 W m^{-2}). Moreover, the correlation coefficient between the IndoPacific anomalies in surface and bottom heat flux per unit area is 0.75 (significant at the 0.05 level) while that between the surface flux and the integrated time rate of change in energy content per unit area is just 0.25 (not distinguishable from 0 correlation). But as for the mean annual cycle, the penetrative radiative flux per unit area has relatively small variations. Thus, the IndoPacific pool analysis suggests that interannual variations in air–pool heat exchange are chiefly balanced by changes in the turbulent ocean flux across the pool boundaries. The situation is much the same for the Atlantic warm water pool (Figure 6C) where the correlation coefficient between the interannual air–pool and inferred, bottom heat flux variations per unit area is 0.71 (again a significant correlation).

3. Discussion

In a related study, Fasullo and Webster (1999) diagnosed the causes of local IndoPacific warm pool SST changes using NCEP air–sea flux estimates in combination with satellite-derived radiation estimates. They report that variations in clouds (that affect incoming solar radiation) and wind (that strongly control the air–sea turbulent fluxes) play major roles in effecting SST change. Similarly, Wang and Enfield (2001, 2002) find evidence for positive ocean–atmosphere feedback involving the radiation balance over the Western Hemisphere Warm Pool. Previously, Enfield and Mayer (1997) invoked weaker evaporation and possibly reduced ocean mixing in response to weaker trade winds to explain Atlantic pool warmings. In light of the apparent inconsistency between the climatological air–sea fluxes and ocean temperature observations, we caution against complete acceptance of these authors' quantitative balances, but would not dispute their general conclusions. Our analyses based on the unadjusted COADS fluxes suggest an important role in the warm pool internal energy budgets for variable turbulent heat flux at pool base on interannual time scale. However, we know of no obvious physical mechanism whereby variable air–pool heat flux might directly cause positively correlated turbulent fluxes at the pool base. If anything, we might expect a negative correlation where times of enhanced ocean cooling by air–sea exchange drove enhanced convective mixing and thus larger vertical heat flux at pool base.

It is of course possible that the air–pool exchanges and turbulent fluxes at pool base vary interannually for different physical reasons, and the fluxes just happen to be correlated on long time scales. Certainly at very long times, the Niiler and Stevenson (1982) mean balance between air–sea and bottom fluxes must be approached. We are, however, rather skeptical that this balance is dominant on interannual time scales and suspect that our inferred turbulent fluxes are dominated by errors in the air–sea flux estimates. But lacking firm uncertainty estimates for the various data products, we can offer no proof based on the present analyses. We note however that our estimated interannual changes in warm pool pseudo-energy content per unit area are just a few W/m^2, which is smaller than the uncertainties typically cited for bulk aerodynamic flux formulae (*e.g.*, Fairall *et al*., 2002). Uncertainty in the accuracy of the COADS flux estimates makes us reluctant to carry out a detailed diagnosis of the pool energy content changes. Rather, we offer the following qualitative discussion focussing on the IndoPacific pool:

During the onset of El Niño in response to reduced easterly wind stress, the tropical sea level and thermocline slopes relax and the warm pool spreads eastward and thins. This process can be initially considered as adiabatic with no change in the warm-pool volume or pseudo-heat content being incurred. But with increased surface area, the pool is more effective at absorbing incoming shortwave solar radiation. The loss of pool energy through sensible and latent heat exchange with the atmosphere may also increase with pool area, though the winds and atmospheric boundary layer properties are also evolving at this time. The ocean temperature data suggest that the radiation gain dominates any sensible and latent losses and pool pseudo-energy content increases to the peak of El Niño. Pool volume also increases at this time, which implies warming of the waters adjacent to the pool boundaries. Reduced winds with corresponding change in sensible and latent heat fluxes could be responsible. Warming of the waters below the pool base could also be important. Downward pool expansion could be the result of increased penetrative short wave radiation through the shallower overlying layers. Convergent turbulent heat flux associated with mixing below the base of the pool is another possible pool-expansion mechanism. Certainly the upper ocean currents are greatly modified during onset of El Niño, though much less clear at present is how the vertical shear and turbulence it supports vary. As the trade winds recover and the ocean–atmosphere system segues into La Niña, the IndoPacific warm pool shrinks. Enhanced atmospheric cooling and stronger turbulent mixing at pool base, both of which can be expected in response to stronger winds, could be responsible for the pool contraction.

The phasing of the warm water pool variations with the SOI that we derived was not expected. Expanding Wyrtki's (1985) idea of a western Pacific buildup precursor to El Niño, Cane *et al.* (1986) suggested that El Niño is preceded by a convergence of waters above the thermocline *throughout* the equatorial Pacific, and that during the events these waters are exported to higher latitudes. Donguy *et al*. (1989), Picaut and Tournier (1991) and Meinen and McPhaden (2000, 2001) have all reported ocean temperature observations that support this sequence. Importantly, much of the equatorial convergence/divergence of surface waters found by these researchers is adiabatic in nature, being associated with planetary wave motions and Ekman transport. Evidently the entire warm water pools, whose evolution is more closely related to air–sea heat fluxes and turbulent mixing, behave differently. Still unclear is if variations in ocean internal energy contained in the entire warm water pools have any direct/active influence on ENSO and tropical Atlantic variability or if the relationships are chiefly with the near-equator waters.

What is evident from our analysis is that further advance in understanding the warm pool energy budgets depends on having air–sea flux and ocean temperature climatologies that are mutually consistent. We note that research on improving air–sea energy fluxes is advancing on several fronts. Notable here are efforts to synthesize diverse data sets as input to improved aerodynamic air–sea heat flux formulae (*e.g.*, Yu *et al.*, 2002 and references therein) and adjoint modeling studies that infer corrections to air–sea fluxes to bring consistency with ocean data (*e.g.*, Stammer *et al.*, 2002). Crudely speaking, our study falls into this latter category. In parallel with work to improve fluxes, it may prove instructive to examine warm pool energy budgets in the context of a coupled ocean–atmosphere numerical model where one can be assured that the air–sea and turbulent fluxes are consistent with the ocean internal energy changes. Although the present state of air–sea heat flux climatologies frustrated our present study, we believe that time-dependent warm pool energy budget analysis constitutes a powerful diagnostic for validating future flux climatologies.

Acknowledgments

This research was supported by the U.S. National Oceanic and Atmospheric Administration through a grant to the Woods Hole Oceanographic Institution and University of Rhode Island. The seasonal cycle computations were carried out while H.-M. Z. was at URI; the interannual analyses were completed after his move to NOAA NESDIS NCDC. Additional support to complete the study came from WHOI's Ocean and Climate Change Institute.

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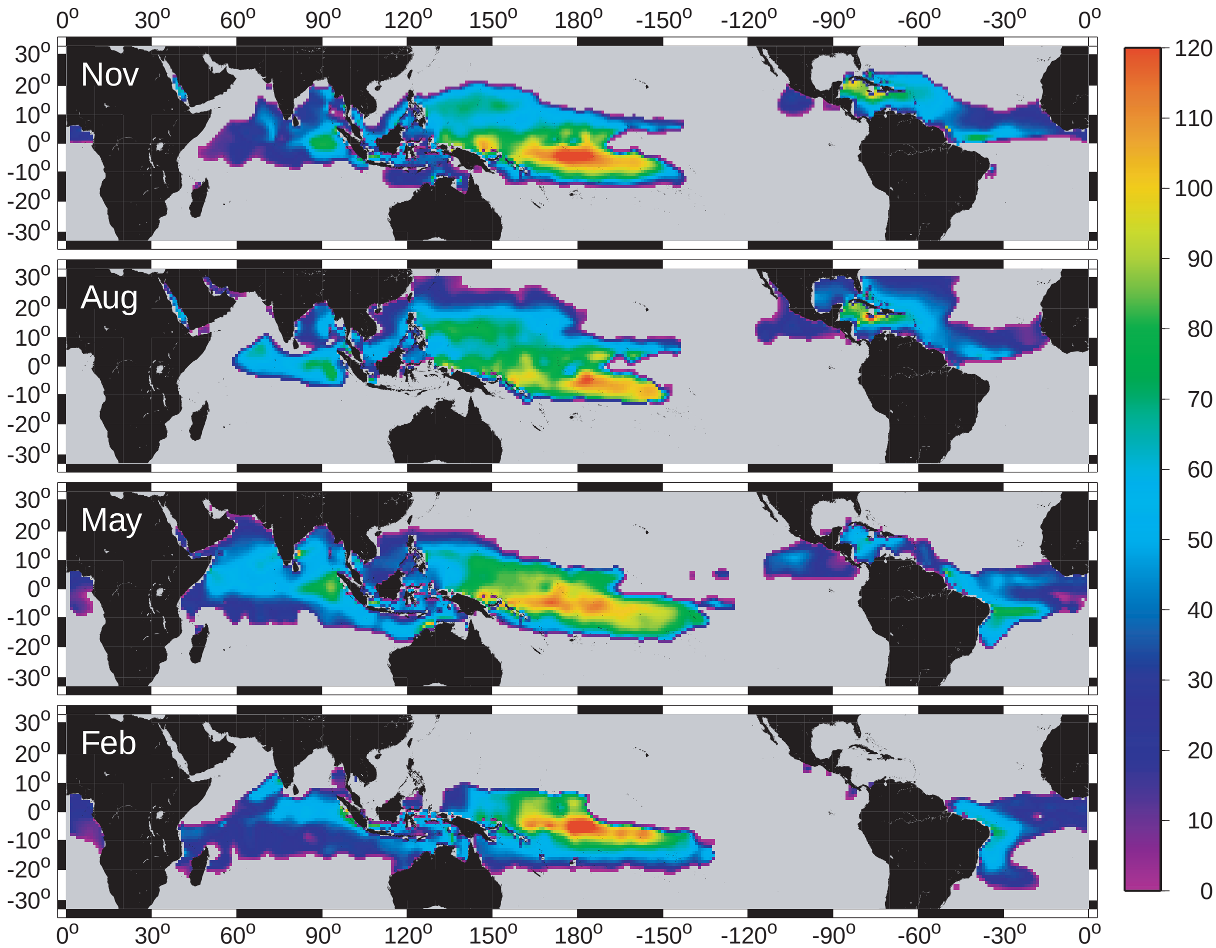

Figure 1. Monthly maps of the warm water pools in the IndoPacific and Atlantic Oceans. Estimated depths of the 28ºC surface (27ºC in the Atlantic) from the WOA98 monthly climatology are contoured for February, May, August, and November.

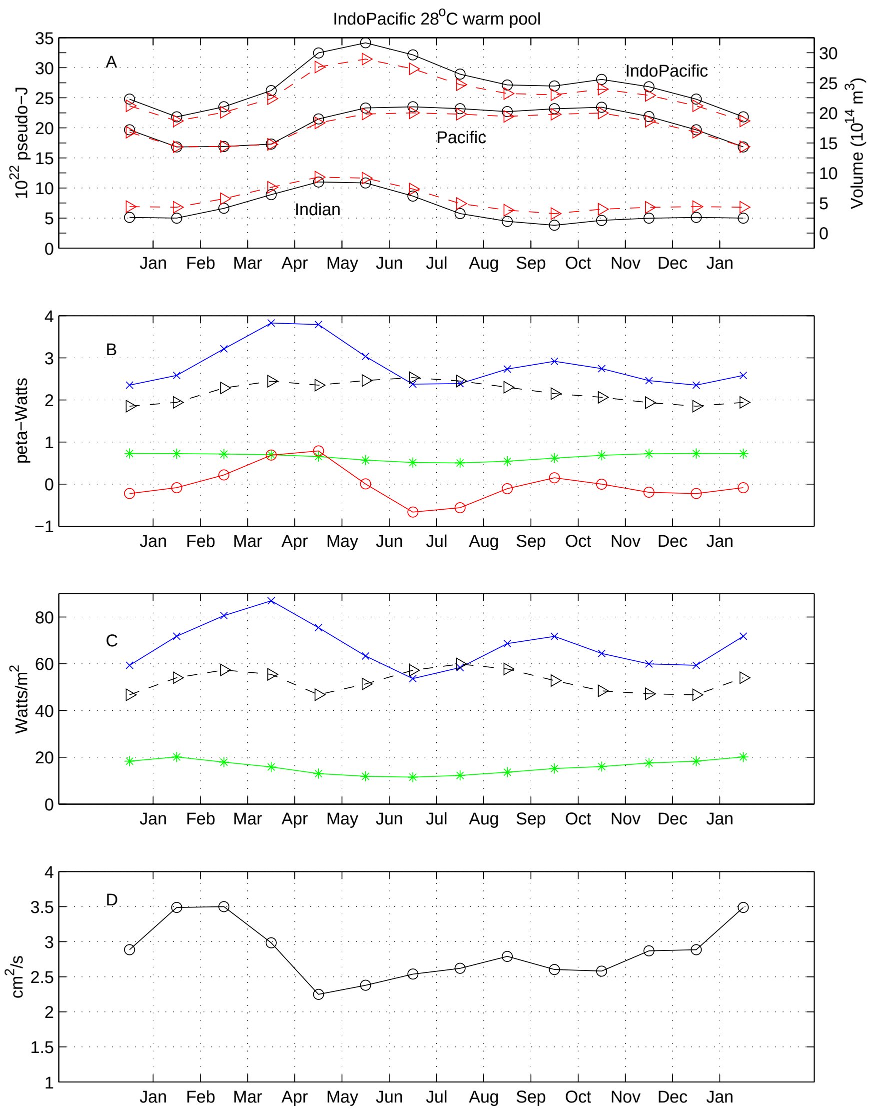

Figure 2. Mean annual cycle of the IndoPacific 28ºC warm water pool. Panel A shows the monthly variations in pool volume (broken line with triangles) and pseudo-heat content based on the Centigrade scale (solid line with open circles). Subdivision of the IndoPacific pool into its Pacific and Indian components was done along the Indonesian island arc. The time labels indicate the start of each month. Panel B gives the monthly estimates of net air–pool heat flux based on the SOC climatology (Josey *et al.*, 1998, x's), the time rate of change of pool energy content (open circles), the estimated penetrative short-wave energy flux across

the pool base (asterisks) and the residual (inferred turbulent heat flux across the pool base plus errors, triangles). A centered time difference was used to estimate the rate of change in pool energy content; the air–sea fluxes were low-pass filtered (.25-.5-.25) for consistency. Panel C shows these quantities normalized by the pool surface area (air–sea exchange: $\times$'s; penetrative radiation: stars; residual: triangles). Panel D shows the estimates of turbulent diffusivity derived from the residual flux per unit area and the mean monthly-averaged vertical temperature gradient at the pool base.

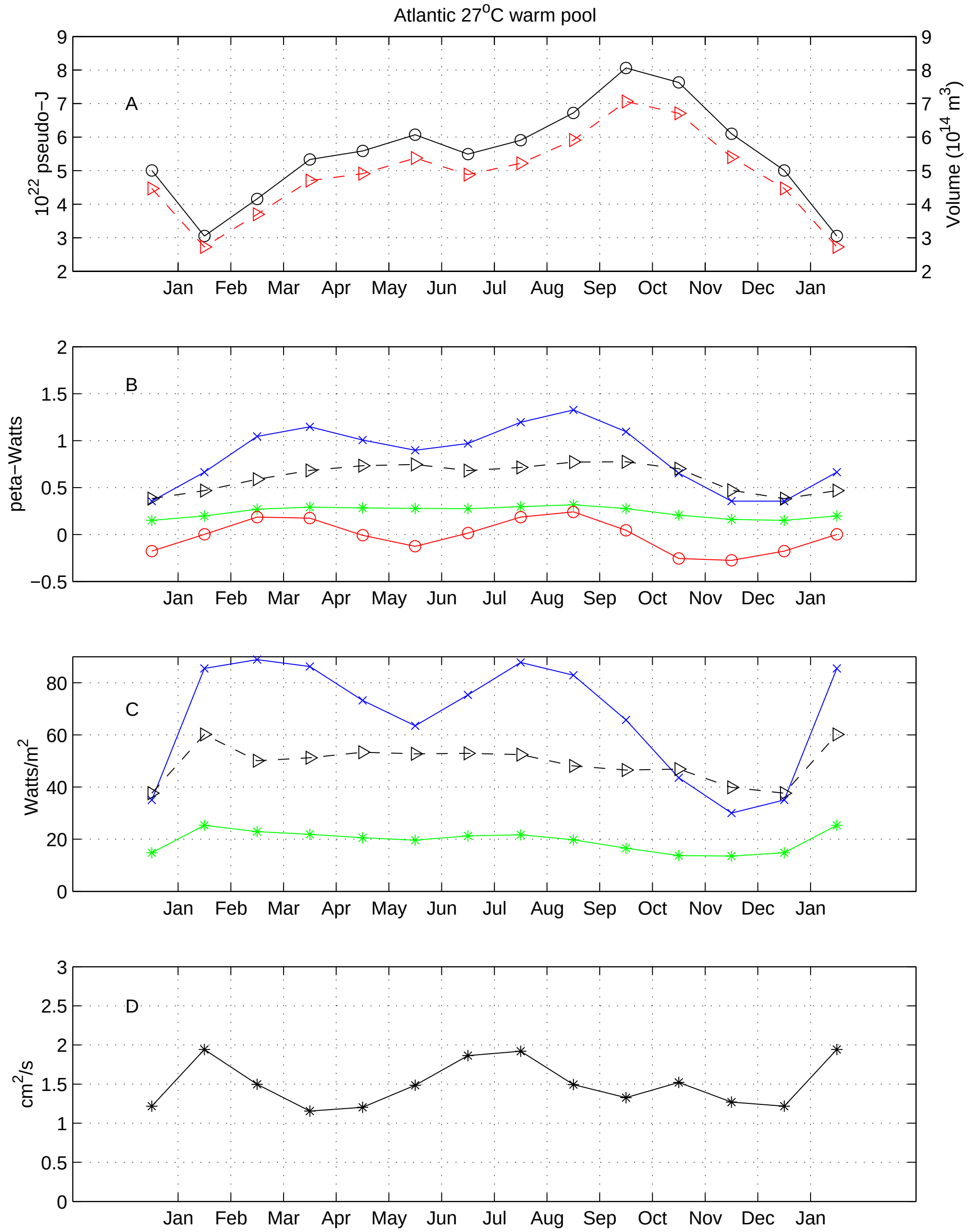

Figure 3. Mean annual cycle of the Atlantic 27ºC warm pool. As in Figure 2, panel A gives the pool volume and pseudo-heat content by month, panels B and C show the net heat fluxes (total and area normalized, respectively) and panel D presents the inferred diffusivities.

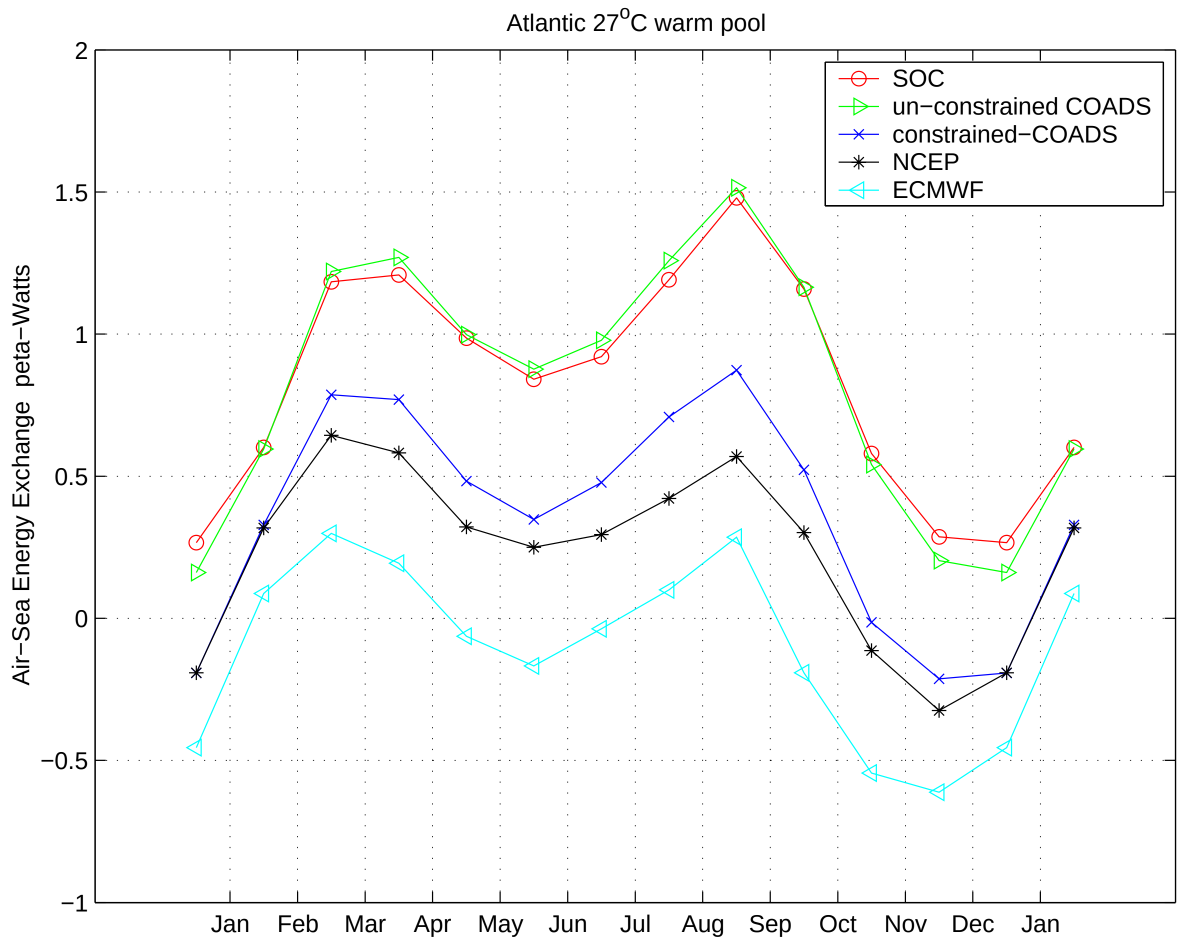

Figure 4. Mean annual cycle of net heat flux from the atmosphere to the Atlantic 27ºC warm water pool based on the SOC and the constrained and unconstrained COADS climatologies, the mean annual cycle of flux estimates based on an NCEP-reanalysis of the period 1979–1998, and a climatology based on ECMWF-reanalysis flux estimates between 1986 and 2000.

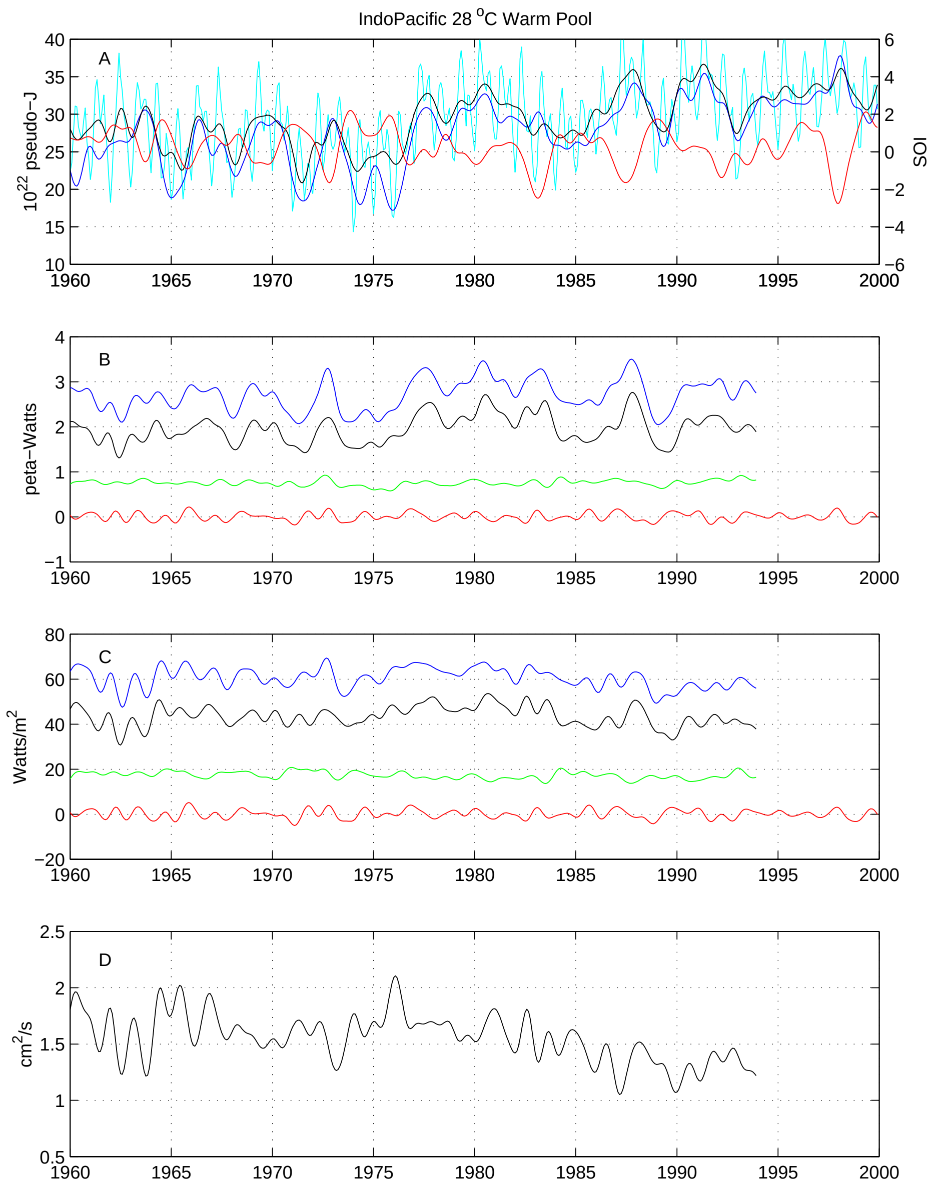

Figure 5. Interannual variations of the IndoPacific 28°C warm water pool energy budget. Panel A shows the low-frequency (filtered to pass periods longer than 1 year) variations in pool pseudo heat content (left side axis labels). The black curve is based on the White climatology while the blue curve is from the Carton *et al.* data base. The cyan curve is the raw monthly energy content values from White (no filtering). Shown in red is the low-pass filtered Southern Oscillation Index (right hand axis). Panel B gives the heat budget terms: blue curve is the area-integrated air-pool heat flux, green curve is the total penetrative

radiative heat flux at pool base, red curve is the area-integrated change in warm pool energy content with time, and the black curve is the inferred total turbulent energy flux across the pool base. Panel C replots these variables after normalizing by pool area while Panel D shows the inferred turbulent diffusivity based on the derived turbulent flux per unit area in Panel C and monthly-averaged temperature gradient at pool base.

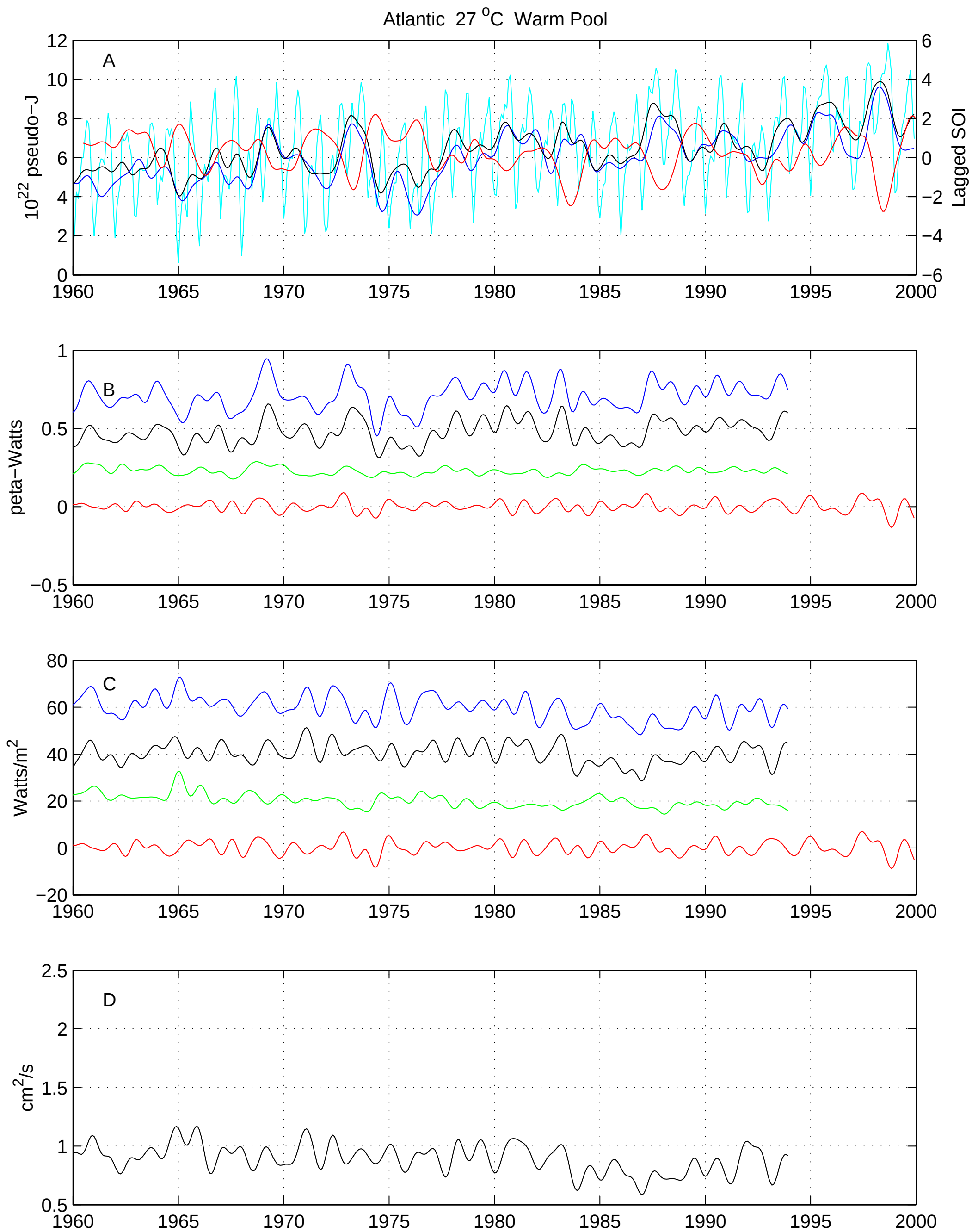

Figure 6. Interannual variations of the Atlantic 27ºC warm pool energy budget. Panels A through D are as described in the caption to Figure 5 except that the SOI curve has been lagged by 6 months.